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Review

The potential to improve culinary herb crop quality with deficit irrigation

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ABSTRACT

Irrigation, the practice of artificially supplementing the water available to crops, accounts for 70% of global freshwater abstractions. Since water supply is increasingly under threat from climate change, implementing novel deficit irrigation techniques - the practice of applying less than the optimum amount of water required by the crop- is a pressing priority for future horticulture. Several studies show that deficit irrigation not only saves water, but may also improve crop quality, for example in fruit trees, wine grapes and culinary herbs such as mint. Here we synthesise current knowledge and practice on irrigation in herb crop production, since dietary trends in recent decades have shown a rise in popularity of fresh produce including culinary herbs, but there has been little progress in developing irrigation techniques and scheduling in such crops. We find strong evidence that water deficit can improve crop quality for several leafy herb crops. This includes increase in essential oils, aroma and quality, alongside increases in the plant metabolites that contribute to antioxidant potential. Despite these positive findings, this review also highlights a gap in understanding the application of deficit irrigation technologies to commercial herb crop systems and suggests further innovation and research is required in this area of precision horticulture.

1. Introduction: issues in water availability

Forty percent of the world's food is produced on just 20% of arable land, enabled by irrigation practices (Ambast et al., 2002; Bastiaanssen, 2000) which account for more than two-thirds of freshwater abstractions worldwide (FAO, 2016). Food security is said to be achieved when the population of more than 7.3 billion people (FAO, 2015) have access to adequate nutrition from food which is safe for consumption. While the human population continues to grow rapidly (an increase of 1.2 billion in the last 10 years) (United Nations, 2015), increased droughts and altered precipitation patterns pose a challenge to food production. Threatening food security, agricultural water deficit and drought arise from insufficient water transport into the rootzone during the growing season, resulting in crop yield losses (Allen et al., 1998).

Application of water for irrigation is generally determined by phenotypic traits of the crop (such as height, roughness of the leaf, ground cover, rooting), the size of area it is produced on and meteorological conditions (such as wind speed, humidity, radiation) (Allen et al., 1998). The objective of irrigation is to construct a system which meets evapotranspiration (ET) requirements by providing adequate moisture in the rootzone without causing detrimental effects of waterlogging (Ambast et al., 2002; Santos et al., 2010). However, the investment in irrigation to combat effects of water deficit stress can be very high, yet often deliver fewer benefits than might be expected (Ambast et al., 2002). Excessive irrigation, leading to water loss through evaporation; run-off and percolation through the soil, or poorly monitored and maintained systems, causing waterlogging and high soil salinity, can also lead to crop stress and damage (Ambast et al., 2002). As a result there has been a rise in interest in deficit irrigation measures which allow crop production with reduced water use (Alcon et al., 2013).

In recent decades changes in human diet, as well as improvements in transport and storage across the western world have led to the increasing popularity of fresh produce including culinary herbs. Though many culinary herbs originate from Mediterranean regions or the Middle East, today they are produced across much of the EU and USA (often in protected environments in temperate climates) with western producers diversifying the available range of herbs as recently as the late 1990 s/early 2000 s. Popular varieties such as basil (*Ocimum basilicum* L.), coriander (*Coriandrum sativum* L.) and parsley (*Petroselinum crispum* L.) continue to be produced in the Middle East, Egypt and Southern America respectively (Peperkamp and Schotel, 2016). Potted herbs may be produced year-round under glass in a range of climates and are often grown on flood benches with excess water applied as an insurance measure. Meanwhile, cut herbs tend to be grown in more

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Mediterranean climates under drip or sprinkler irrigation. Drip irrigation is deemed to be more efficient as it applies water directly to the rootzone, compared to spraying across the area with sprinkler irrigation, potentially applying water to unimportant areas or losing water to wind currents. Regardless of the method, use of freshwater for these purposes exacerbates existing water availability issues in these areas. In order to continue supporting recent dietary trends, irrigation practices must be adjusted to reduce water use but without detriment to herb crop production.

2. Water use in plants and the impacts of deficit

Water is responsible for sustained turgor in plants as well as having roles as a solvent and as a component in biochemical processes (Stagnari et al., 2014). Water deficit occurs when there is an imbalance between ET of the plant and transport of water into the root-soil profile (Lipiec et al., 2013). During reproductive stages (from flowering onwards), water deficit stress can cause premature flower drop and poor seed and fruit filling. In aromatic crops, such as culinary herbs, changes in composition or yield of essential oils may also be observed (Jeshni et al., 2015; Petropoulos et al., 2008).

Responses to water deficit can vary considerably between and among species and may be morphological or biochemical (Lizana et al., 2006), as summarised in Fig. 1. Morphological coping mechanisms include altered leaf morphologies, such as narrow leaves and high trichome densities (Picotte et al., 2007), or alterations to root structure, such as long tap roots (Gibbens and Lenz, 2001). These traits act to reduce water loss from leaf surfaces and enhance water uptake from the roots. Other responses may include: a rapid reduction in growth, attributed to inhibition of cell expansion (Tari et al., 2008); changes to gas exchange and assimilation translocation (Lizana et al., 2006; Stagnari et al., 2014; Tari et al., 2008); alterations to water uptake and ET; development of thicker palisade tissue (Fang and Xiong, 2015); or reduced cell differentiation and expansion, producing smaller, harder leaves which has the benefit of reducing susceptibility of the product to bruising during packing, but these traits have not, to our knowledge, been quantified in culinary herbs.

Short-term water deficits may induce a decrease in root hydraulic conductivity (RHC) which is the ease of which water can move through pores and be drawn up into and through the roots. This effect is attributed to the activity of aquaporins (Lipiec et al., 2013); the water channels in cell membranes of most living organisms (Chaumont and Tyerman, 2014), which tightly control transcellular water movement in plants. A more persistent drought is likely to further decrease RHC, accompanied by an influx of suberin into the root endodermis (Lipiec et al., 2013) which acts as a barrier to solutes, increasing the selectivity of plant solute uptake. Long term drought will decrease RHC further still as xylem embolism occurs, whereby sap flow is interrupted by air bubbles which are sucked into xylem vessels (Lipiec et al., 2013). This reduction in RHC reduces water going into the shoot but also helps to reduce total water loss (Lipiec et al., 2013).

A reduction in stomatal conductance (g_s) is one of the most rapid responses to water deficit, resulting in decreased transpiration. Stomata are central to the regulation of gas exchange by opening and closing in response to the external environment and internal signalling. Abscisic acid (ABA) is a key regulator involved in plant signalling (Daszkowska-Golec and Szarejko, 2013) and is widely accepted as crucial to stomatal closure under water deficit conditions (McAdam and Brodribb, 2016; McAdam et al., 2016). Synthesised in plastids and cytosol of both roots and shoots (Daszkowska-Golec and Szarejko, 2013; Pantin et al., 2013), ABA generates two physiological responses to water deficit in plants. Firstly, by decreasing permeability of the vascular bundle sheath to water (Negin and Moshelion, 2016; Pantin et al., 2013) and, secondly, by stimulating a cascade of reactions when ABA is delivered to the guard cell, which lead to a decrease in stomatal aperture (Daszkowska-Golec and Szarejko, 2013). Stomatal conductance is also determined to some extent by the size and density of stomata for the given species in any given environment as dictated by changes in CO_2, light, temperature, water and nutrient availability and is positively correlated with stomatal size and negatively correlated with stomatal density (Sun et al., 2014).

There are generally three, sometimes distinct, coping strategies employed by plants to deal with drought: (i) ***escape***, in which the plant completes its growth cycle during the rainy season; (ii) ***avoidance***, where the plant can withstand periods of water deficit by maintaining substantial water content within tissues and (iii) ***tolerance***, in which the plant can continue to function with reduced tissue water content. Leafy crops tend to be less tolerant to water deficit compared to other plant types, e.g. woody crops such as fruit trees (Xu and Leskovar, 2014). Cabbage (*Brassica oleracea*) is a leafy crop with a shallow root system, which is intermediately sensitive to water deficit stress (FAO, 2015). However, Xu and Leskovar (2014) were able to implement 75% ET to *B. oleracea* with little impact on plant size; leaf characteristics and gas exchange; head size and weight and leaf pigment content, suggesting that there could be potential to cut down water inputs in other leafy crops, such as culinary herbs, too.

3. Artificial application of water to crops

All methods of irrigation: ***flood, spray*** and ***drip*** (Table 1) (USGS,

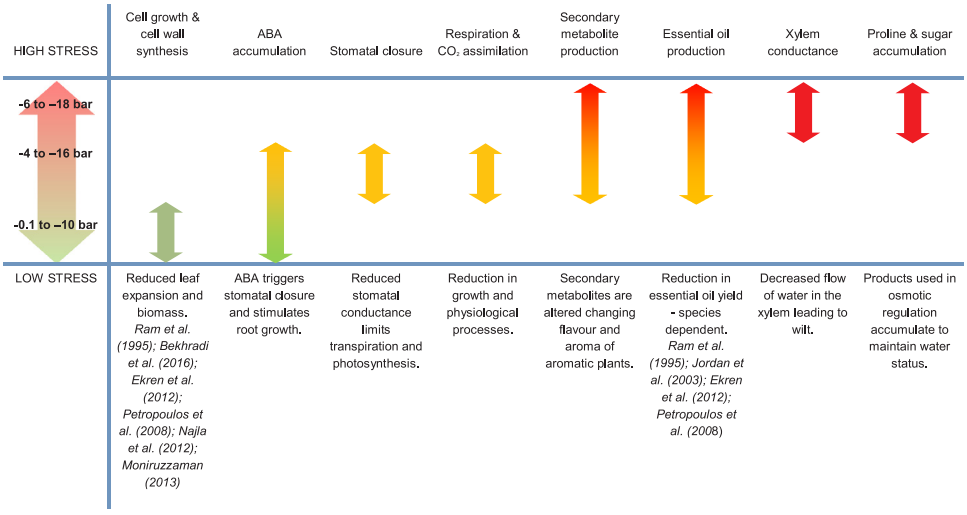
HIGH STRESS
Cell growth & cell wall synthesis
ABA accumulation
Stomatal closure
Respiration & CO_2 assimilation
Secondary metabolite production
Essential oil production
Xylem conductance
Proline & sugar accumulation
-6 to –18 bar
-4 to –16 bar
-0.1 to –10 bar
LOW STRESS
Reduced leaf expansion and biomass. Ram et al. (1995); Bekhradi et al. (2016); Ekren et al. (2012); Petropoulos et al. (2008); Najla et al. (2012); Moniruzzaman (2013)
ABA triggers stomatal closure and stimulates root growth.
Reduced stomatal conductance limits transpiration and photosynthesis.
Reduction in growth and physiological processes.
Secondary metabolites are altered changing flavour and aroma of aromatic plants.
Reduction in essential oil yield - species dependent. Ram et al. (1995); Jordan et al. (2003); Ekren et al. (2012); Petropoulos et al. (2008)
Decreased flow of water in the xylem leading to wilt.
Products used in osmotic regulation accumulate to maintain water status.

Fig. 1. The effects of water deficit stress under decreasing water potential and related studies (adapted from Hsiao, 1973).

Table 1
Benefits and downfalls of different irrigation methods.

Irrigation method	Pros	Cons	Use in culinary herb production
Flood	Simple and effective	Inefficient; cannot reach elevated parts of field (or bench); run off, often leading to eutrophication; percolation through soil; soil surface can be washed away, degrading the land	Surface irrigation of *C. sativum* had comparable results to high pressure drip irrigation (Lal et al., 2015).
Spray	Can cover different size areas; reaches all levels of field	Can be carried away by wind currents; promotes mildew and disease of the shoot.	Increased occurrence of downy mildew in O. basilicum (Garibaldi et al., 2007).
Drip	More efficient method than flood and spray as applies water directly to the rootzone	Not very straightforward or adaptable installation; potential to promote root pest and disease if used with inappropriate drainage.	Low-pressure drip irrigation impacted on yield of C. sativum (Lal et al., 2015), but can be effective at reducing disease occurrence with careful management.

2016), have been applied to herb crop production though the technique used depends on the style of the output, i.e. potted or cut; outdoor or protected; as well as the scale of production. In glasshouse environments flood and drain (or 'ebb and flow') benches are likely to be employed for the production of potted fresh herbs, while irrigation for herb production of cut varieties in the field may be drip or sprinkler, which can be applied by a pivot or boom and reel system. In both in- and outdoor systems, sprinkler techniques may be used on young herbs while their root system is underdeveloped and the shoot is in early stages of development.

Lal et al. (2015) grew coriander (*Coriandrum sativum*) under both surface irrigation and high or low pressure drip irrigation and, while finding no significant effect on leaf length and number, harvest height or branch number, did find a significant reduction in number of umbellets (part of the flower cluster) with low pressure drip irrigation when grown in a protected environment. Meanwhile, Marouelli et al. (2013) found sprinkler irrigation to have the additional benefit of reducing the spore number and therefore occurrence of powdery mildew, while drip irrigation reduced shoot disease by avoiding wetting of the shoot, but favoured soil pathogens, particularly where drainage was deemed insufficient.

4. Limiting water application to crops

Optimum irrigation strategies aim to maximise yield per unit of water applied to the crop (Akhtar et al., 2013) but this type of management may become unsustainable, as water for irrigation is projected to become increasingly scarce. Increased water productivity in both rain-fed and irrigated systems is required and by using precision agriculture techniques, we can avoid excessive water use (Petropoulos et al., 2008) and the accompanying problems of water logging and increased soil salinity (Petropoulos et al., 2009). Deficit irrigation tightly controls dose and timing of watering (Alcon et al., 2013; Garg and Dadhich, 2014), intentionally supplying the crop with less than ET (Alcon et al., 2013; Garg and Dadhich, 2014) in order to impose a mild stress on the crop (Alizadeh and Mousavi, 2013). This practice requires knowledge of crop response to drought stress and identification of different growth stages in order for it to be successfully applied (Alcon et al., 2013). While it may result in reduced yields (Garg and Dadhich, 2014; Homayounfar et al., 2014), the reduction is negligible in comparison to the water saving and other economic gains (Alizadeh and Mousavi, 2013), e.g. reducing canopies in fruit trees and therefore the extent of management usually required. Furthermore, deficit irrigation has been shown to improve crop quality (Alcon et al., 2013). As the studies here show, there are three key methods of applying deficit irrigation and all three aim to exploit plant responses to water deficit, allowing the reduction of inputs while maintaining quality and yield as much as possible (Neal et al., 2010).

4.1. Sustained deficit irrigation (SDI)

Sustained deficit irrigation (SDI) is the application of less than 100% crop ET to the growing crop, meaning the deficit becomes greater as the crop matures, (as crop water requirement increases with crop growth). Sharma et al. (2014) applied a sustained deficit (100% ET vs 50% ET) via drip irrigation on three cultivars of melon (*Cucumis melo*). While 'Super Nectar' suffered 43% yield losses, 'Da Vinci' yield loss was only 30% and 'Mission' 24%, but quality was improved by increases in total soluble solids and beta-carotene levels (Sharma et al., 2014), which results in sweeter, more vibrantly coloured fruit. Early to mid-season sustained deficits applied to peanut maintained a stable yield, without alteration to quality (Rowland et al., 2012), while reducing the levels of irrigation from overhead sprinklers to spearmint (*Mentha spicata*) reduced biomass but maintained uniform oil content (Okwany et al., 2012). Success with SDI has also been found in two Australian wine grapes by Chalmers et al. (2010) who significantly reduced irrigation levels in Cabernet Sauvignon and Shiraz grapes (*Vitis spp.*). Benefits of deficit included increases in wine colour which were attributed to either flavonoid biosynthesis or changes in anthocyanin chemical properties (Chalmers et al., 2010).

4.2. Regulated deficit irrigation (RDI)

Regulated deficit irrigation (RDI) relies on phenological knowledge of the crop to be irrigated as irrigation is scheduled for crucial growing stages, for example grain filling in wheat (*Triticum* spp.). Faci et al. (2014) found they could produce a high yield of good quality grapes (*Vitis vinifera*) by applying 100% irrigation until the onset of ripening, before reducing irrigation by 20–40% until harvest. Applying irrigation water in two parts reduced berry cracking, the result of too much water applied during maturation and a common and costly issue in the grape industry (Faci et al., 2014). Ballester et al. (2014) investigated the long term effects (six growing seasons) of RDI on Clementina de nules (*Citrus spp.*) and found that while there was a reduction in fruit growth, it was not proportionate to the amount of deficit applied and fruit quality was improved with increases in soluble solids (e.g. sugars, amino acids, pectins) and titratable acidity. Another benefit of deficit in fruit trees is reduced management costs due to a reduction in pruning weight, here as much as 20% (Ballester et al., 2014). This benefit was also found in Red Beaut plum (*Prunus spp.*) trees by Samperio et al. (2015), who also found ~20% reduction in pruning weight.

4.3. Partial rootzone drying (PRD)

Partial rootzone drying (PRD) takes advantage of root to shoot signalling by allowing one side of the root zone to dry down while the other is watered, alternating sides as the zone dries. PRD uncouples root-to-shoot signalling from hydraulic properties of the plant, with the dry part of the rootzone triggering water deficit responses in the shoot via signalling, while the availability of water from the irrigated zone allows the continuation of biochemical processes and maintains shoot turgor. A study in 2008, investigated the anthocyanin composition and accumulation in Cabernet sauvignon (*V. vinifera*) under PRD and the crop benefitted from increased wine colour density, tannin and

Table 2
Impacts of deficit irrigation techniques on various fresh produce.

Species	Deficit	Effect	Reference
Cucumis melo L. cv. Da Vinci and Mission	50% ETc	24—43% reduction in marketable yield due to a reduction in fruit size; increased root length density in Da Vinci; increased soluble solids content and water use efficiency with increased deficit in both varieties	Sharma et al. (2014)
Arachis hypogaea L.	50% and 75% of commercially applied irrigation, applied at different stages in the growth cycle	10—26% reduction in yield when 50% commercial application is introduced late in the season; applying deficit early in the season, followed by full irrigation for the rest of the season has no negative impact on the final product; increased root growth when commercial irrigation is halved	Rowland et al. (2012)
Mentha spicata L.	5 levels of irrigation from 5% ETc to 100% ETc	Decreased yield with increased deficit; no impact on oil yield in the first harvest, but reduced oil yield in the second cut due to lower regrowth in dry areas	Okwany et al. (2012)
Vitis vinifera L. cv. Cabernet and Shiraz	70, 52 & 43% ETc (Cabernet) and 65, 45 & 34% ETc (Shiraz)	Increase in wine colour with increased deficit, attributed to either changes in flavonoids or chemical properties of anthocyanins	Chalmers et al. (2010)
Vitis vinifera L. cv. Autumn Royal and Crimson	60% and 80% of net irrigation requirements until fruit ripening	Maintained yield in Autumn Royal, but reduced yield in Crimson; fruit quality maintained but significant colour change in Crimson	Faci et al. (2014)
Citrus clementina cv. Clementina de Nules	35% and 50% ETc over six growing seasons	Increase in soluble solids and titratable acidity with increase in deficit, but ~20% decrease in pruning weight over the seasons	Ballester et al. (2014)
Prunus salicina Lindl. Cv. Red Beaut	30% and 60% ETc during post-harvest seasons	No effect on productivity but a decrease in pruning weight	Samperio et al. (2015)
Vitis vinifera L. cv. Cabernet Sauvignon	40% delivered via partial rootzone drying	15% increase in wine colour density, polymeric pigment, total tannin and total anthocyanins	Bindon et al. (2008)
Gossypium hirsutum	> 70% of commercial irrigation	84– 92% reduction in yield, but better quality fibers, generating higher price	Tang et al. (2005)

polymeric pigment (Bindon et al., 2008). Stoll et al. (2000) measured a 10-fold increase in abscisic acid content of *Vitis spp*. roots in the dry portion of the rootzone when irrigated with PRD, which was accompanied by a significant decrease in g_s (Stoll et al., 2000), thus reducing water loss by transpiration from the leaves. This method has also been applied in cotton (*Gossypium spp*.) by alternating watering of furrows between crop rows. While deficit reduced yield, it produced better quality fibres that can be sold for a higher price (Tang et al., 2005) (Table 2).

5. Limiting water application to herb crops

5.1. Deficit irrigation in herbs Reducing irrigation water use during production has been shown to increase oil yields of mint, palmarosa and lemongrass, without impact on oil quality

Aromatic plants have been cultivated for uses in medicine, fragrances, food and beverages for centuries, with their antioxidant (Brewer, 2011) and phenolic (Gülçin et al., 2009) content more recently becoming of increasing interest.

There are a multitude of studies investigating herb crops, including (but not limited to): use and safety as a medicinal ingredient (Aissaoui et al., 2011; Furletti et al., 2011; Ramirez Reyes et al., 2010); oil extraction techniques (Lachowicz et al., 1997) and antioxidant properties (Brewer, 2011; Dorman and Hiltunen, 2011; Dorman et al., 2009; Il-Suk et al., 2011; Nkomo et al., 2011). Studies into water use are limited but are by no means non-existent. Bergamot mint (*Mentha citrata*) is a succulent crop which has a high water requirement in the summer and is harvested for its linalool and linalyl acetate-rich essential oil. Ram et al. (1995) investigated the impact of different irrigation levels on Bergamot mint, determined by irrigation water: cumulative pan evaporation (IW: CPE), finding 1.2 IW: CPE to be optimum for both herb and oil yields. Singh et al. (1997) obtained highest herb and oil yields of Palmarosa (*Cymbopogon martinii*) at 0.5 IW:CPE, with no impact on the quality of the oil, but with highest water use efficiency (WUE – here determined by essential oil yield produced per unit of water applied) at 0.1 IW:CPE. A later, similar, experiment on lemongrass (*Cymbopogon flexuosus*) found highest yields at 0.7 IW: CPE and an inverse oil/irrigation relationship with no impact on the quality of the oil (Singh et al., 2000). Jordan et al. investigated the effect of irrigation levels on *Thymus hyemalis* (Jordan et al., 2003) by using local ET to implement deficit irrigation levels and produced better oil quality, in terms of thymol content, when irrigated with 40% ET, but requiring 80% ET in the spring. *Thymus zygis* produced a greater essential oil ratio at 30% ET with lower watering levels significantly increasing essential oil ratios and demonstrating a similar relationship in levels of radical scavenging activity (Jordan et al., 2009).

5.2. Deficit in basil Antioxidant capacity of basil has been shown to increase when the crop is grown under deficit irrigation

Early work on basil (*Ocimum basilicum*) focused extensively on its yield and essential oil components, with little focus on irrigation. Field experiments in the Mediterranean climate of Turkey by Ekren et al. (2012) applied four different irrigation treatments to purple basil (*O basilicum* var. purpurascens) over a period with no rain and temperatures of around 30 °C. Plants were irrigated below the surface at 50%, 75% and 125% field capacity (FC) with a 100% FC control. When grown to full flower, plants demonstrated an increase in average essential oil ratio but decreases in height and yield (Ekren et al., 2012). Bekhradi et al. (2016) implemented deficit irrigation (50% and 75% FC plus 100% FC control) to three cultivars: purple, green and Genovese (a common commercial variety). The study also found reduced yield; and loss was considerably higher in the Genovese variety (-40% compared with -26% in green) which was the highest yielding variety under control conditions (Bekhradi et al., 2016). The green variety grown at 50% FC had the highest antioxidant capacity while the lowest was found in control plants (Bekhradi et al., 2016) suggesting mild deficit has potential to improve crop quality in *O. basilicum*.

Salt stress induces many of the same physiological and biochemical responses in plants as drought by mimicking osmotic stress (Bashtanova and Flowers, 2012). Barbieri et al. (2012) exposed two different *O. basilicum* cultivars (Genovese and Napoletano) to salt stress with the aim to demonstrate that a reduction in g_s induces salinity tolerance and water use efficiency under salt stress. Barbieri et al. (2012) did not find significantly altered volatile oils, but acknowledging that it has been found elsewhere, determined this effect as species-specific and dependent on both intensity and length of time the stress is imposed. However, they did find in the unstressed Napoletano variety, a significantly higher g_s than Genovese due to 74% lower stomatal density in Genovese (Barbieri et al., 2012). A further experiment aiming to determine WUE (here determined as plant production per water used) was conducted under controlled conditions in a growth chamber but stomatal responses were not replicated here, though the lower stomatal density of

Genovese compared to Napoletano was confirmed and g_s of the former was always lower than the latter. Overall, this made Genovese a more water use efficient cultivar but only significantly when under salt stress (Barbieri et al., 2012), suggesting potential to exploit WUE of some *O. basilicum* cultivars with water or salt stress, or a combination of both.

Though work on water use in *O. basilicum* is not extensive, it is known that volatile isoprenoids provide protection against abiotic stress (such as water deficit) and the *Lamiaceae* family, which includes *O. basilicum*, contain large amounts of such compounds in their essential oils (Barbieri et al., 2012). Genovese, green and purple Iranian landraces grown under water deficit conditions demonstrated a depleted volatile profile over time on the shelf (Jordan et al., 2017), but other studies, also on a purple landrace (*O. basilicum* pupurescens), found water deficit stress not only to alter the ratio of constituents in that oil but also to increase overall essential oil ratio (Ekren et al., 2012). Though increased oil levels are deemed to be a positive consequence, the change in constituents is likely to impact taste and flavour; two important factors in the food and fresh herb industries.

5.3. Deficit in parsley Vitamin concentration, carotenes and anthocyanins can be increased with negligible impact on yield, when grown under a deficit irrigation regime

Petropoulos et al. aimed to determine the effects of water deficit (Petropoulos et al., 2008) and salinity (Petropoulos et al., 2009) on three varieties of parsley (*Petroselinum spp*.), including the popular culinary varieties: curly (*P. crispum* var. crispum) and flat (*P. crispum* var. neapolitanum) leaf. To implement water deficit, irrigation was withheld until the soil reached 30–45% FC or 45–60% FC (levels 1 and 2 respectively) and control was maintained at 0–10% FC. Disruption to metabolic processes including photosynthesis and respiration caused *P. crispum* var. crispum to exhibit progressive decreases in fresh weight, while *P. crispum* var. neapolitanum exhibited decreases at 30–40% FC, but not further at 45–60% (Petropoulos et al., 2008).

A more recent study from Najla et al. (2012) also examined the effects of water stress on *P. crispum* var. crispum and var. neapolitanum and found the effects of water deficit were greater in *P. crispum* var. crispum compared with *P. crispum* var. neapolitanum, with a considerably greater decrease in stem length and leaf area and significantly greater increase in stem diameter (Najla et al., 2012). Reduction in leaf area impedes light interception by the plant, while stem diameter changes according to osmotic pressure and diurnal cycles however it, along with changes in stem length, can be an acclimation response to drought. Of the deficits imposed (10%, 30% and 50% FC plus 100% control), 50% FC did not significantly reduce weight, but did induce an increase in anthocyanins, carotenes and vitamin concentrations (Najla et al., 2012), suggesting that reducing irrigation in a *Petroselinum* crop may not only save water, but improve crop quality and nutritional value, with negligible impact on yield.

Of particular interest in the Petropoulos studies (Petropoulos et al., 2008, 2009) was the impact of the given stress on the yield and composition of essential oils. Both *P. crispum* var. crispum and var. neapolitanum exhibited increases in oil yield when subjected to water deficit, but only *P. crispum* var. crispum significantly increased on m^2 basis; a factor of importance to the essential oil industry. Additionally, the composition of *P. crispum* var. crispum oil was altered, with a decrease in myristicin, but increases in α- and β-phellandrene, terpindene and ρ-cymenene (Petropoulos et al., 2008). Water deficit increased myristicin in *P. crispum* var. neapolitanum, but reduced 1, 3, 8-ρ-methariene and terpinolene + ρ-cymanene (Petropoulos et al., 2008). Meanwhile, increasing concentrations of sodium chloride (NaCl) increased essential oil concentration in *P. crispum* var. crispum, but did not alter concentrations in *P. crispum* var. neapolitanum (Petropoulos et al., 2009). It seems, therefore, that the quality of the oil may not be affected but flavour and aroma may be altered, which are key criteria of interest to the food and fresh herb industries, as well as important factors to the consumer when they select their fresh produce.

5.4. Deficit in coriander Regulated deficit irrigation has been successfully applied to coriander, increasing water use efficiency and improving the quality of the oil

The effects of phosphorus levels on *C. sativum* under three different irrigation levels were investigated by Hani et al. (2015). Highest yields were achieved where crops were irrigated with 100% ET compared to 50 or 75%. Unlukara et al. (Unlukara et al., 2016) similarly found increasing irrigation levels had a positive effect on oil yield in two coriander varieties in comparison with rain-fed crops. Nonetheless, studies in recent years have successfully applied deficit irrigation at different developmental stages of *C. sativum*, usually with the focus on improving essential oil quality and/or quantity. Nadjafi et al. (2009) terminated irrigation at start of blooming; at start of flowering or start of seed formation and found differences in umbels per plant, seed number and essential oil ratio, with the highest for all three found when irrigation terminated at seed formation. The high level of essential oil ratio is likely related to seed number, but oil quality was also increased with an increase in linalool and pentadecanone; the two key constituents found in the four land races studied (Nadjafi et al., 2009).

Moniruzzaman et al. (2013) conducted a deficit experiment withholding irrigation for a combination of stages: no irrigation; branching stage; branching and flowering stages; branching and seed filling stages and branching, flowering and seed filling stages. Irrigation increased height, branch number, seed and umbel number as well as delaying bolting and increasing harvest index. However, deficit at branching stage demonstrated the greatest WUE (here determined as irrigation efficiency) (Moniruzzaman et al., 2013). Both studies were focused on seed production while the current interest is in the production of leafy herbs for culinary use and neither of these studies give a figure for how much water was applied at each irrigation event, nor can it be determined if it is the level of deficit or the stage at which it was applied as each treatment is not represented individually. Nonetheless, they suggest that deficit may increase WUE and oil quality in *C. sativum* crops.

It is known that short periods of stress can protect a plant from more prolonged stress later in its life cycle and also that salt and water deficit stress induce many similar responses in plants (Bashtanova and Flowers, 2012). As one of the most problematic of the popular herbs, in terms of shelf life, Bashtanova and Flowers (2012) gave *C. sativum* a pre-harvest NaCl or sodium sulphate (Na_2SO_4) treatment in an attempt to extend shelf life. Preliminary studies determined that the plants were more sensitive to NaCl than Na_2SO_4 thus the authors proceeded with drought experiments using Na_2SO_4 (Bashtanova and Flowers, 2012). While most of the untreated plants exhibited quick wilting and droopy petioles as is often seen on the shelf, a majority of plants pre-treated with 12.5 mM Na_2SO_4 exhibited drought avoidance. The extended shelf life of treated plants was reflected in their upright appearance after five days in conditions mimicking a supermarket shelf. With four accessions studied, improvements in shelf life induced by mild salt stress ranged from 50 to 120% increase. The plants were also more water use efficient as they assimilated the same amounts of CO_2 as control plants but at lower g_s (Bashtanova and Flowers, 2012).

6. Conclusion: application of concepts

We can conclude from studies applying water deficit to a host of herb crops:

- A primary benefit of increasing essential oil yield, with a positive impact on quality; an effect which enhances taste and aroma.
- While some reduction in height and yield have been found in *O.*

basilicum, so have increases in essential oils and antioxidant capacity, producing a better quality plant that may be more manageable when it comes to packing.

- In two popular varieties of parsley, *P. crispum* var. crispum and var. neapolitanum, the response to water deficit is negligible when it comes to yield but is accompanied by beneficial increases in vitamins, anthocyanins, carotenes and oil yield and quality.
- *Coriandrum sativum* also produced better quality oil, as well as improved WUE and extended shelf life.
- While current irrigation techniques may be varied, studies to date suggest SDI and RDI are more applicable to culinary herbs than techniques such as PRD, though this method is by no means redundant.

The literature on water use and irrigation in herb crops is still limited with significant gaps for future study. Here, we have identified the potential to save water with benefits to crop quality in numerous culinary herb crops, including mint, thyme and lemongrass, but with particular focus on market favourites basil, coriander and parsley. However, identifying key water deficit stress responses in these species and in the different environments in which they are grown remains a priority if they are to be produced using deficit irrigation. Despite these gaps, research has consistently demonstrated that introducing this practice in culinary herb production offers an advantage to the consumer, of a crop with increased health benefits which can also be more aromatic and full of flavour. Furthermore, this is an unexploited opportunity for the producer to reduce water use and, indirectly, energy use and costs, while maintaining high quality in the crop.

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References

Aissaoui, A., Zizi, S., Israili, Z.H., Lyoussi, B., 2011. Hypoglycemic and hypolipidemic effects of Coriandrum sativum L. in Meriones shawi rats. J. Ethnopharmacol. 137, 652–661. https://doi.org/10.1016/j.jep.2011.06.019.

Akhtar, F., Tischbein, B., Awan, U.K., 2013. Optimizing deficit irrigation scheduling under shallow groundwater conditions in lower reaches of Amu Darya river basin. Water Resour. Manag. 27, 3165–3178.

Alcon, F., Egea, G., Nortes, P.A., 2013. Financial feasibility of implementing regulated and sustained deficit irrigation in almond orchards. Irrig. Sci. 31, 931–941. https://doi.org/10.1007/s00271-012-0369-6.

Alizadeh, H., Mousavi, S.J., 2013. Coupled stochastic soil moisture simulation-optimization model of deficit irrigation. Water Resour. Res. 49, 4100–4113.

Allen, R.G., Pereira, Luis S., Raes, D., Smith, M., 1998. Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and drainage paper 56.

Ambast, S.K., Keshari, A.K., Gosain, A.K., 2002. Satellite remote sensing to support management of irrigation systems: concepts and approaches. Irrig. Drain. 51, 25–39. https://doi.org/10.1002/ird.26.

Ballester, C., Castel, J., El-Mageed, Abd, Castel J.R., T.A., Intrigliolo, D.S., 2014. Long-term response of “Clementina de Nules” citrus trees to summer regulated deficit irrigation. Agric. Water Manag. 138, 78–84. https://doi.org/10.1016/j.agwat.2014.03.003.

Barbieri, G., Vallone, S., Orsini, F., Paradiso, R., De Pascale, S., Negre-Zakharov, F., Maggio, A., 2012. Stomatal density and metabolic determinants mediate salt stress adaptation and water use efficiency in basil (Ocimum basilicum L.). J. Plant. Physiol. 169, 1737–1746. https://doi.org/10.1016/j.jplph.2012.07.001.

Bashtanova, U.B., Flowers, T.J., 2012. Effect of low salinity on ion accumulation, gas exchange and postharvest drought resistance and habit of Coriandrum sativum L. Plant. Soil. 355, 199–214. https://doi.org/10.1007/s11104-011-1093-3.

Bastiaanssen, W.G.M., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin. Turk. J. Hydrol. 229, 87–100. https://doi.org/10.1016/s0022-1694(99)00202-4.

Bekhradi, F., Delshad, M., Marín, A., Luna, M.C., Garrido, Y., Kashi, A., Babalar, M., Gil, M.I., 2016. Effects of salt stress on physiological and postharvest quality characteristics of different Iranian genotypes of basil. Hortic. Environ. Biotechnol. 56, 777–785. https://doi.org/10.1007/s13580-015-1095-9.

Bindon, K., Dry, P., Loveys, B., 2008. Influence of partial rootzone drying on the composition and accumulation of anthocyanins in grape berries (Vitis vinifera cv. Cabernet Sauvignon). Aust. J. Grape Wine Res. 14, 91–103. https://doi.org/10.1111/j.1755-0238.2008.00009.x.

Brewer, M.S., 2011. Natural antioxidants: sources, compounds, mechanisms of action and potential applications. Compr. Rev. Food Sci. Food Saf. 10, 221–247.

Chalmers, Y.M., Downey, M.O., Krstic, M.P., Loveys, B.R., Dry, P.R., 2010. Influence of sustained deficit irrigation on colour parameters of Cabernet Sauvignon and Shiraz microscale wine fermentations. Aust. J. Grape Wine Res. 16, 301–313. https://doi.org/10.1111/j.1755-0238.2010.00093.x.

Chaumont, F., Tyerman, S.D., 2014. Aquaporins: highly regulated channels controlling plant water relations. Plant. Physiol. 164, 1600–1618. https://doi.org/10.1104/pp.113.233791.

Daszkowska-Golec, A., Szarejko, I., 2013. Open or close the gate - stomata action under the control of phytohormones in drought stress conditions. Front. Plant. Sci. 4. https://doi.org/10.3389/fpls.2013.00138.

Dorman, H.J.D., Hiltunen, R., 2011. Antioxidant and pro-oxidant in vitro evaluation of water-soluble food-related botanical extracts. Food Chem. 129, 1612–1618. https://doi.org/10.1016/j.foodchem.2011.06.017.

Dorman, H.J.D., Kosar, M., Baser, K.H.C., Hiltunen, R., 2009. Phenolic profile and antioxidant evaluation of Mentha x piperita L., (Peppermint) extracts. Nat. Prod. Commun. 4, 535–542.

Ekren, S., Sönmez, Ç., Özçakal, E., Kurttaş, Y.S.K., Bayram, E., Gürgülü, H., 2012. The effect of different irrigation water levels on yield and quality characteristics of purple basil (Ocimum basilicum L.). Agric. Water Manag. 109, 155–161. https://doi.org/10.1016/j.agwat.2012.03.004.

Faci, J.M., Blanco, O., Medina, E.T., Martinez-Cob, A., 2014. Effect of post veraison regulated deficit irrigation in production and berry quality of Autumn Royal and Crimson table grape cultivars. Agric. Water Manag. 134, 73–83. https://doi.org/10.1016/j.agwat.2013.11.009.

Fang, Y., Xiong, L., 2015. General mechanisms of drought response and their application in drought resistance improvement in plants. Cell. Mol. Life Sci. 72, 673–689. https://doi.org/10.1007/s00018-014-1767-0.

FAO, 2015. Crop Water Information. (Accessed 28 May 2018). http://www.fao.org/land-water/databases-and-software/crop-information/en/.

FAO, 2016. Water Withdrawal by Sector, Around 2007. AQUASTAT Database. (Accessed 28 May 2018). http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en.

Furletti, V.F., Teixeria, I.P., Obando-Pereda, G., Mardegan, R.C., Sartoratto, A., Figueira, G.M., Duarte, R.M., Rehder, V.L., Duarte, M.C., Hofling, J.F., 2011. Action of Coriandrum sativum L. Essential oil upon Oral candida albicans biofilm formation. Evid.-Based Complement. Altern. Med. 1–9 2011.

Garg, K., Dadhich, S.M., 2014. Integrated non-linear model for optimal cropping pattern and irrigation scheduling under deficit irrigation. Agric. Water Manag. 140, 1–13.

Garibaldi, A., Bertetti, D., Gullino, M.L., 2007. Effect of leaf wetness duration and temperature on infection of downy mildew (*Peronospora sp.*) of basil. J. Plant Dis. Prot. 114, 6–8. https://doi.org/10.1007/bf03356196.

Gibbens, R.P., Lenz, J.M., 2001. Root systems of some Chihuahuan Desert plants. J. Arid Environ. 49, 221–263. https://doi.org/10.1006/jare.2000.0784.

Gülçin, I., Elmastaş, M., Aboul-Enein, H.Y., 2009. Determination of antioxidant and radical scavenging activity of basil (Ocimum basilicum L. family Lamiaceae) assayed by different methodologies. Phyther. Res. 21, 354–361.

Hani, M.M., Hussein, S.-A.A.H.A., Mursy, M.H., Ngezimana, W., Mudau, F.N., 2015. Yield and essential oil response in coriander to Water stress and phosphorus fertilizer application. J. Essent. Oil Bear. Plants 18, 82–92. https://doi.org/10.1080/0972060x.2014.974080.

Homayounfar, M., Lai, S.H., Zomorodian, M., Sepaskhah, A.R., Ganji, A., 2014. Optimal crop Water allocation in case of drought occurrence, imposing deficit irrigation with proportional cutback constraint. Water Resour. Manag. 28, 3207–3225.

Hsiao, T.C., 1973. Plant Responses to Water Stress. Annu. Rev. Plant Physiol. 24, 519–570.

Il-Suk, K., Mi-Ra, Y., Ok-Hwan, L., Suk-Nam, K., 2011. Antioxidant activities of Hot Water extracts from various spices. J. Mol. Sci. (International Ed.) 12, 4120–4131. https://doi.org/10.3390/ijms12064120.

Jeshni, M.G., Mousavinik, M., Khammari, I., Rahimi, M., 2015. The changes of yield and essential oil components of German Chamomile (Matricaria recutita L.) under application of phosphorus and zinc fertilizers and drought stress conditions. J. Saudi Soc. Agric. Sci. https://doi.org/10.1016/j.jssas.2015.02.003.

Jordan, M.J., Martinez, R.M., Cases, M.A., Sotomayor, J.A., 2003. Watering level effect on Thymus hyemalis Lange essential oil yield and composition. J. Agric. Food Chem. 51, 5420–5427. https://doi.org/10.1021/jf034335m.

Jordan, M.J., Martinez, R.M., Martinez, C., Monino, I., Sotomayor, J.A., 2009. Polyphenolic extract and essential oil quality of Thymus zygis ssp gracilis shrubs cultivated under different watering levels. Ind. Crops Prod. 29, 145–153. https://doi.org/10.1016/j.indcrop.2008.04.021.

Jordan, M.J., Quilez, M., Luna, M.C., Bekhradi, F., Sotomayor, J.A., Sanchez-Gomez, P., Gil, M.I., 2017. Influence of water stress and storage time on preservation of the fresh volatile profile of three basil genotypes. Food Chem. 221, 169–177. https://doi.org/10.1016/j.foodchem.2016.10.059.

Lachowicz, K.J., Jones, G.P., Briggs, D.R., Bienvenu, F.E., Palmer, M.V., Mishra, V., Hunter, M.M., 1997. Characteristics of plants and plant extracts from five varieties of basil (Ocimum basilicum L) grown in Australia. J. Agric. Food Chem. 45, 2660–2665. https://doi.org/10.1021/jf960791h.

Lal, G., Singh, B., Maheria, S.P., 2015. Influence of protected environments and irrigation methods on plant growth and seed yield of coriander (Coriandrum sativum). Indian J. Agric. Sci. 85, 60–64.

Lipiec, J., Doussan, C., Nosalewicz, A., Kondracka, K., 2013. Effect of drought and heat stresses on plant growth and yield: a review. Int. Agrophys. 27, 463–477. https://doi.

org/10.2478/intag-2013-0017.
Lizana, C., Wentworth, M., Martinez, J.P., Villegas, D., Meneses, R., Murchie, E.H., Pastenes, C., Lercari, B., Vernieri, P., Horton, P., Pinto, M., 2006. Differential adaptation of two varieties of common bean to abiotic stress - I. Effects of drought on yield and photosynthesis. J. Exp. Bot. 57, 685–697. https://doi.org/10.1093/jxb/erj062.
Marouelli, W.A., da Costa Lage, D.A., Gravina, C.S., Michereff Filho, M., de Souza, R.B., 2013. Sprinkler and drip irrigation in the organic tomato for single crops and when intercropped with coriander. Rev. Cienc. Agron. 44, 825–833.
McAdam, S.A.M., Brodribb, T.J., 2016. Linking turgor with ABA biosynthesis: implications for stomatal responses to vapor pressure deficit across Land plants. Plant. Physiol. 171 (2008–2016). https://doi.org/10.1104/pp.16.00380.
McAdam, S.A.M., Brodribb, T.J., Ross, J.J., 2016. Shoot-derived abscisic acid promotes root growth. Plant. Cell. Environ. 39, 652–659. https://doi.org/10.1111/pce.12669.
Moniruzzaman, M., Rahman, M.M., Hossain, M.M., Karim, A.J.M.S., Khaliq, Q.A., 2013. Effect of irrigation on seed yield and yield attributes of coriander (Coriandrum sativum L.). Bull. Inst. Trop. Agric. Kyushu Univ. 36, 35–43.
Nadjafi, F., Damghani, A.M.M., Ebrahimi, S.N., 2009. Effect of irrigation regimes on yield, yield components, content and composition of the essential oil of Four Iranian Land races of Coriander (Coriandrum sativum). J. Essent. Oil Bear. Plants 12, 300–309.
Najla, S., Sanoubar, R., Murshed, R., 2012. Morphological and biochemical changes in two parsley varieties upon water stress. Physiol. Mol. Biol. Plants 18, 133–139. https://doi.org/10.1007/s12298-012-0105-y.
Neal, J.S., Fulkerson, W.J., Campbell, L.C., 2010. Differences in yield among annual forages used by the dairy industry under optimal and deficit irrigation. Crop Pasture Sci. 61, 625–638. https://doi.org/10.1071/cp09216.
Negin, B., Moshelion, M., 2016. The evolution of the role of ABA in the regulation of water-use efficiency: from biochemical mechanisms to stomatal conductance. Plant. Sci. 251, 82–89. https://doi.org/10.1016/j.plantsci.2016.05.007.
Nkomo, M., Nkeh-Chungag, B.N., Kambizi, L., Ndebia, E.J., Sewani-Rusike, C., Iputo, J.E., 2011. Investigation of the antinociceptive and anti-inflammatory properties of Heteromorpha Arborescens (Apiaceae). African J. Tradit. Complement. Altern. Med. 8, 412–419. https://doi.org/10.4314/ajtcam.v8i4.11.
Okwany, R.O., Peters, T.R., Ringer, K.L., Walsh, D.B., Rubio, M., 2012. Impact of sustained deficit irrigation on spearmint (Mentha spicata L.) Biomass production, oil yield, and oil quality. Irrig. Sci. 30, 213–219. https://doi.org/10.1007/s00271-011-0282-4.
Pantin, F., Monnet, F., Jannaud, D., Costa, J.M., Renaud, J., Muller, B., Simonneau, T., Genty, B., 2013. The dual effect of abscisic acid on stomata. New. Phytol. 197, 65–72. https://doi.org/10.1111/nph.12013.
Peperkamp, M., Schotel, P., 2016. Product Factsheet: Fresh Herbs in Europe. CBI Market Intelligence. https://www.cbi.eu/sites/default/files/market_information/researches/product-factsheet-europe-fresh-herbs-2016_final_approved.pdf.
Petropoulos, Sa., Daferera, D., Polissiou, M.G., Passam, H.C., 2008. The effect of water deficit stress on the growth, yield and composition of essential oils of parsley. Sci. Hortic. (Amsterdam) 115, 393–397. https://doi.org/10.1016/j.scienta.2007.10.008.
Petropoulos, S.A., Daferera, D., Polissiou, M.G., Passam, H.C., 2009. The effect of salinity on the growth, yield and essential oils of turnip-rooted and leaf parsley cultivated within the Mediterranean region. J. Sci. Food Agric. 89, 1534–1542. https://doi.org/10.1002/jsfa.3620.
Picotte, J.J., Rosenthal, D.M., Rhode, J.M., Cruzan, M.B., 2007. Plastic responses to temporal variation in moisture availability: consequences for water use efficiency and plant performance. Oecologia 153, 821–832. https://doi.org/10.1007/s00442-007-0794-z.
Ram, M., Ram, D., Singh, S., 1995. Irrigation and nitrogen requirements of bergamot mint on a sandy loam soil under subtropical conditions. Agric. Water Manag. 27, 45–54. https://doi.org/10.1016/0378-3774(95)91231-u.
Ramirez Reyes, M., Reyes-Esparza, J., Torres Angeles, O., Rodriguez-Fragoso, L., 2010. Mutagenicity and safety evaluation of Water extract of Coriander sativum leaves. J. Food Sci. 75, T6–T12. https://doi.org/10.1111/j.1750-3841.2009.01403.x.
Rowland, D.L., Faircloth, W.H., Payton, P., Tissue, D.T., Ferrell, J.A., Sorensen, R.B., Butts, C.L., 2012. Primed acclimation of cultivated peanut (Arachis hypogaea L.) through the use of deficit irrigation timed to crop developmental periods. Agric. Water Manag. 113, 85–95. https://doi.org/10.1016/j.agwat.2012.06.023.
Samperio, A., Henar Prieto, M., Blanco-Cipollone, F., Vivas, A., Jose Monino, M., 2015. Effects of post-harvest deficit irrigation in “Red Beaut” Japanese plum: tree water status, vegetative growth, fruit yield, quality and economic return. Agric. Water Manag. 150, 92–102. https://doi.org/10.1016/j.agwat.2014.12.006.
Santos, C., Lorite, I.J., Tasumi, M., Allen, R.G., Fereres, E., 2010. Performance assessment of an irrigation scheme using indicators determined with remote sensing techniques. Irrig. Sci. 28, 461–477. https://doi.org/10.1007/s00271-010-0207-7.
Sharma, S.P., Leskovar, D.I., Crosby, K.M., Volder, A., Ibrahim, A.M.H., 2014. Root growth, yield, and fruit quality responses of reticulatus and inodorus melons (Cucumis melo L.) to deficit subsurface drip irrigation. Agric. Water Manag. 136, 75–85. https://doi.org/10.1016/j.agwat.2014.01.008.
Singh, S., Ram, M., Ram, D., Sharma, S., Singh, D.V., 1997. Water requirement and productivity of palmarosa on sandy loam soil under a sub-tropical climate. Agric. Water Manag. 35, 1–10. https://doi.org/10.1016/s0378-3774(97)00038-3.
Singh, S., Ram, M., Ram, D., Singh, V.P., Sharma, S., Tajuddin, 2000. Response of lemongrass (Cymbopogon flexuosus) under different levels of irrigation on deep sandy soils. Irrig. Sci. 20, 15–21. https://doi.org/10.1007/s002710000026.
Stagnari, F., Galieni, A., Speca, S., Pisante, M., 2014. Water stress effects on growth, yield and quality traits of red beet. Sci. Hortic. (Amsterdam) 165, 13–22. https://doi.org/10.1016/j.scienta.2013.10.026.
Stoll, M., Loveys, B., Dry, P., 2000. Hormonal changes induced by partial rootzone drying of irrigated grapevine. J. Exp. Bot. 51, 1627–1634. https://doi.org/10.1093/jexbot/51.350.1627.
Sun, Y., Yan, F., Cui, X., Liu, F., 2014. Plasticity in stomatal size and density of potato leaves under different irrigation and phosphorus regimes. J. Plant. Physiol. 171, 1248–1255. https://doi.org/10.1016/j.jplph.2014.06.002.
Tang, L.S., Li, Y., Zhang, J.H., 2005. Physiological and yield responses of cotton under partial rootzone irrigation. F. Crop. Res. 94, 214–223. https://doi.org/10.1016/j.fcr.2005.01.005.
Tari, I., Camen, D., Coradini, G., Csiszar, J., Fediuc, E., Gemes, K., Lazar, A., Madosa, E., Mihacea, S., Poor, P., Postelnicu, S., Staicu, M., Szepesi, A., Nedelea, G., Erdei, L., 2008. Changes in chlorophyll fluorescence parameters and oxidative stress responses of bush bean genotypes for selecting contrasting acclimation strategies under water stress. Acta Biol. Hung. 59, 335–345. https://doi.org/10.1556/ABiol.59.2008.3.7.
United Nations, 2015. The World Population Prospects: 2015 Revision. (Accessed 28 May 2018). http://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html.
Unlukara, A., Beyzi, E., Ipek, A., Gurbuz, B., 2016. Effects of different water applications on yield and oil contents of autumn sown coriander (Coriandrum sativum L.). Turkish J. F. Crop. 21, 200–209. https://doi.org/10.17557/tjfc.46160.
USGS, 2016. The USGS Water Science School: Irrigation Techniques. (accessed 28 May 2018). http://water.usgs.gov/edu/irmethods.html.
Xu, C., Leskovar, D.I., 2014. Growth, physiology and yield responses of cabbage to deficit irrigation. Hortic. Sci. 41, 138–146.